PB86-177193

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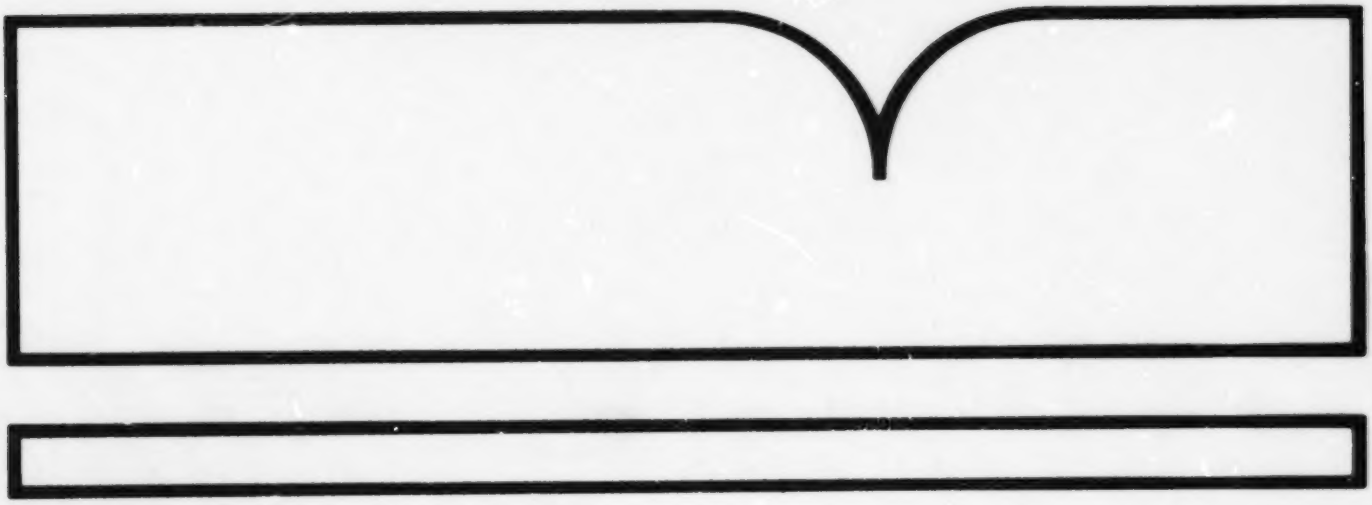
Hawaii Univ. at Manoa, Honolulu

Prepared for

Environmental Monitoring Systems Lab.
Research Triangle Park, NC

Apr 86



U.S. Department of Commerce
National Technical Information Service
NTIS

PB 86-177193

EPA/600/D-86/069
April 1986

TEST OF A THEORETICAL COMMUTER EXPOSURE MODEL TO VEHICLE EXHAUST IN TRAFFIC

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U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA/600/D-86/069	2.	3. RECIPIENT'S ACCESSION NO. PB86 177193/AS
4. TITLE AND SUBTITLE Test of a Theoretical Commuter Exposure Model to Vehicle Exhaust in Traffic		5. REPORT DATE April 1986
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Peter Flachsbart, Assoc. Prof., Univ. of Hawaii Clayton Ah Yo, M.S. Candidate, Univ. of Hawaii		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Hawaii at Manoa Department of Urban & Regional Planning Porteus 107 Honolulu, HI 96822		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. CR-810344-01-4
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Montoring Systems Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/08

15. SUPPLEMENTARY NOTES

P O: Harold Sauls, EMSL/RTP 629-2347

16. ABSTRACT

A theoretical model of commuter exposure is presented as a box or cell model with the automobile passenger compartment representing the microenvironment exposed to CO concentrations resulting from vehicle exhaust leaks and emissions from traffic. Equations which describe this situation are developed and discussed. The model is evaluated according to predictive power, explanatory power when compared to a more parsimonious model, and the influence of initial CO concentrations inside a vehicle's passenger compartment.

The model is shown to have relatively high predictive power and excellent explanatory power when compared to the more conservative model.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	18
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

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INTRODUCTION

Mathematical models of commuter exposure to motor vehicle exhaust are based either on theoretical algorithms of pollutant dispersion or on empirically derived relationships. Theoretical models can be tailored to conditions on a roadway that affect pollutant dispersion. Ingalls[1] calls these specific conditions "microscale situations," such as tunnels, street canyons, and open roadways. For open roadways Ingalls used a line source model to describe the concentration, which affects the commuter, from traffic traveling on the opposite side of the highway. This was added to the concentration from vehicles traveling in the same direction by using a Gaussian plume equation applied to multiple point sources. Similarly, Simmon and Patterson[2] used a methodology based on the CALINE3 dispersion model to compute concentrations on open roadways. In this model, the concentration at the receptor was equal to the sum of concentrations contributed by different elements of the roadway. Each element was treated as a finite line source whose concentration was approximated by a Gaussian crosswind finite line source equation. Some of the early empirical models were developed in attempts to explain concentrations at locations exterior to and within vehicles in terms of meteorological variables, ambient air quality, traffic volumes, and emissions from motor vehicles on the roadway.[3,4,5] In general, these existing theoretical and empirical models assume that a commuter's exposure inside a vehicle is about equal to the roadway concentration.

A few of the more recent studies of commuter exposure have questioned the assumption that vehicular concentrations are identical to roadway concentrations under all situations. Petersen and Sabersky[6] and Petersen and Allen[7] found that concentrations inside the vehicle were about the same or slightly less than outside concentrations regardless of the "comfort state" (ventilation setting) of the vehicle. Petersen and Sabersky also observed rapid variations, caused by passing cars, in concentrations outside of a traveling vehicle. However, concentrations measured inside showed only gradual change. Colwill and Hickman[8] found that average concentrations measured inside of 11, new small cars of different make were 35 to 75 percent of average outside concentrations. Their study also showed that differences in internal concentrations were more pronounced between vehicles than they were between different runs in the same vehicle. This result was attributed to differences in ventilation systems, which affected the ratio of inside to outside concentrations.

Ott and Willits[9] used a box model of pollutant dispersion in an enclosed space to describe the concentration inside an automobile. They showed that the concentration within a car built up gradually over time until it reached an equilibrium with the outside concentration. The rate at which the inside concentration approached the outside concentration was the "time constant", T. In their study the time constant was influenced by window settings and vehicle speeds, qualities which affect air flow rates through the vehicle. They demonstrated mathematically that when exposures were averaged over a period of time much greater than the time constant of the vehicle, the interior concentration equaled the exterior concentration.

In the study of personal exposure to air pollution, Duan[10] refers to a microenvironment as a "chunk of air space with homogeneous pollutant concentration". This paper first presents a theoretical discussion of a microenvironmental model of commuter exposure to motor vehicle exhaust in traffic, using carbon monoxide (CO) as an indicator of exhaust. It then describes the Washington Commuter Microenvironment Study,[11] which provided data to test the theoretical model. In that study commuter exposure data were collected using personal monitors equipped with data loggers. The paper then presents an application and an evaluation of the theoretical model using data collected from the Washington Study. The paper concludes with some implications for future research.

As an indicator pollutant, CO is appropriate and amenable to the study of commuter exposure for several reasons. First, motor vehicles in general, and automobiles in particular, are responsible for almost all the CO emissions in cities.[12] Second, CO is a nonreactive pollutant, which means that the complex, chemical reactions that could occur between emission from a source and a receptor's exposure would not have to be considered.[13] Third, the spatial variability of CO concentrations makes exposure to this pollutant more amenable to monitoring using personal exposure monitors (PEM's) than fixed-site ambient air monitors, as demonstrated in previous studies of roadway microenvironments.[14,15] Finally, Ott, et al.[16] assert that CO is capable of being a surrogate measure of other auto-related pollutants, such as nitrogen oxides, carbonaceous particulate and associated organics, nitrosamines, and formaldehyde.

THEORETICAL MODEL OF COMMUTER EXPOSURE

The vehicle microenvironment is defined by the passenger compartment of the vehicle. Within this interior volume, the commuter is exposed to CO from three major sources: passenger smoking, vehicle exhaust system leaks, and emissions from traffic. A model that can describe the CO concentrations within the vehicle from these three sources is the box or cell model.

Box or cell models have been applied in air pollution literature to describe the concentration within volumes where the concentration is uniform in the vertical direction and transport is controlled primarily by advection. These models are based on the principle of conservation of mass: The total mass of an air pollutant within a volume is equal to the balance of the mass entered, exited, emitted, and reacted within that volume. Based on this principle, the change in mass within the vehicle over time is equal to the infiltration rates minus the exhaust rates plus the internal rate of production:[17]

$$\frac{d(C(t)V)}{dt} = \sum_{j=1}^{J} C_j(t)F_j(t) - C(t) \sum_{k=1}^{K} F_k(t) + P(t) \qquad (1)$$

(The variables are described in the list of symbols on page 16.) Note that because CO is chemically inert, the effect of chemical reactions with other pollutants may be ignored and their terms have been excluded from the expression.

Equation (1) may be simplified under the following three conditions. First, it is assumed that there are no CO emissions within the car during the commute, ($P(t) = 0$), since this paper focuses on an explanation of commuter exposure due to emissions entering the vehicle from the roadway. Second, for the case where the vehicle is travelling through a single roadway microenvironment, one can assume that the concentration throughout that microenvironment is homogeneous. Therefore, the concentration entering the vehicle at any entry, j, is equal to the roadway microenvironment's concentration, ($C_j(t) = C_R$, for all j). Third, to prevent buildup of atmospheric pressure within the vehicle, the total flow rate of air into the vehicle (F_j) must equal the total flow rate of air that exits the vehicle (F_k). Therefore, the entry and exit flow rates can be replaced by a single flow rate (F) representing the rate at which air flows through the vehicle.

Given the conditions expressed in the previous paragraph, Equation (1) becomes:

$$\frac{d(C(t)V)}{dt} = C_R F - C(t)F \tag{2}$$

Similar terms on the same side of the equation can be aggregated by adding C(t) to both sides of the equation. In addition, the derivative can be isolated by dividing through by the vehicle's volume, which was a constant for the Washington Study. The resulting relationship is expressed below:

$$\frac{d(C(t))}{dt} + \frac{F}{V} C(t) = \frac{F}{V} C_R \tag{3}$$

Papacostas[18] notes that this expression is a first order linear differential equation that may be solved by first multiplying both sides of the equation by the integrating factor, $e^{(F/V)t}$. By doing this, the left hand side of Equation (3) becomes an exact differential and the relationship is transformed into:

$$\frac{d(C(t)e^{(F/V)t})}{dt} = C_R e^{(F/V)t} \tag{4}$$

One can solve for the concentration within the vehicle, C(t), by integrating Equation (4) with respect to t and dividing both sides by the exponential term:

$$C(t) = C_R + Ge^{-(F/V)t} \tag{5}$$

Given the CO concentration within the vehicle is C(0) when it enters the roadway microenvironment (t=0), the constant of integration, G, is expressed by:

$$G = C(0) - C_R \tag{6}$$

Substituting Equation (6) into (5), one then obtains a model that describes the CO concentration within the vehicle as a function of time:

$$C(t) = C_R + (C(0) - C_R)e^{-(F/V)t} \tag{7}$$

By rearranging terms, one can isolate the contributions to the interior concentration made by the roadway and by the initial concentration in the vehicle when it enters the roadway microenvironment:

$$C(t) = C_R(1 - e^{-(F/V)t}) + C(0)e^{-(F/V)t} \quad (8)$$

The rate at which the inside concentration approaches the outside concentration is influenced by the ratio of the flow through the vehicle to the volume, (F/V). Ott and Willits described this ratio as the inverse of a "time constant" for the vehicle:[9]

$$F/V = 1/T \quad (9)$$

Since (V/F) is in units of time, T is in units of time.

When T is small relative to the time the vehicle spends in the roadway microenvironment, C(t) approaches C_R quickly. When T is large relative to t, C(t) grows slowly, suggesting that C_R may contribute little to the concentration inside the vehicle, C(t). The time constant (T) is proportional to the volume of the vehicle and inversely proportional to the rate at which air flows through the vehicle. If the ventilation rate is large relative to the volume of the vehicle, then the time constant will be small. Conversely, if the ventilation rate is small relative to the volume, then the time constant will be large.

The relationship for the concentration inside of the vehicle at some time, t, can be expressed as a function of the time constant by substituting 1/T into Equation (8):

$$C(t) = C_R(1 - e^{-t/T}) + C(0)e^{-t/T} \quad (10)$$

The average exposure (E) in a microenvironment can be expressed by:

$$E = (1/t_a)\int_0^{t_a} C(t)\, dt \quad (11)$$

Substituting Equation (10) for C(t) in Equation (11) and letting the averaging time equal the time that the vehicle is within a roadway microenvironment ($t_a = t_R$), the relationship between the average commuter exposure (E) and CO concentrations within the vehicle is described by:

$$E = (1/t_R)\int_0^{t_R} [C_R(1 - e^{-t/T}) + C(0)e^{-t/T}]\, dt \quad (12)$$

Integrating the above equation with respect to, t, and collecting common terms, we obtain a relationship that describes the average exposure of a commuter in a vehicle traveling within a roadway microenvironment:

$$E = C_R + (T/t_R)(C(0) - C_R)(1 - e^{-t_R/T}) \quad (13)$$

If the vehicle is on the roadway for a very long time relative to the time constant ($t_R >> T$), the ratio of the time constant to the travel

time on the roadway approaches zero ($T/t_R \approx 0$) and the commuter's average exposure approaches the CO concentration on the roadway:

$$E = C_R \qquad (14)$$

Since equation (14) is much more parsimonious than Equation (13), it is more attractive to utilize. Whether the theoretical model in Equation (13) describes variation in average CO exposure better than Equation (14) is an issue to be evaluated later in the paper.

METHODOLOGY OF THE WASHINGTON STUDY

The Washington Study provided automobile commuter exposure to CO along 8 hypothetical routes (Figure 1). Collectively, the 8 routes extended 258 km or 8.6% of metropolitan Washington's 2,984 km of arterials and freeways in 1980.[19] Each route, which ranged in length from 15 to 44 km, was divided into links of roughly 0.8 to 4.8 km. The 108 links of the commuter exposure study corresponded to roadway segments used in a commuter travel time study sponsored by the National Capital Region Transportation Planning Board.[20]

A hypothetical automobile commuter trip from home to work was constructed for each route for the morning rush-hour period (7:00 to 9:30 a.m.) with a return trip during the evening period (4:30 to 6:30 p.m.). The evening route generally traced the morning route in reverse order with some exceptions to accommodate links that were one-way streets. Parking garages provided the terminus for the morning commute and the origin for the evening commute for two of the routes.

During the 6-week survey period from January 17 through March 4, 1983, each route was surveyed on every other workday of a standard workweek. A starting time window (e.g., 1 hr.) was defined for each route so that the survey of that route could be completed within the rush-hour period. Each time window was then subdivided into uniform intervals (e.g., 10 min.). The actual starting time for each trip on any given date was chosen randomly to simulate different starting times among commuters.

The commuting was done by technicians employed by Battelle Columbus Laboratories, an EPA contractor. Five vehicles of the same type (1983 Chevrolet Malibu) were used by Battelle to minimize variation in CO exposure due to differences in ventilation systems among autos. To further minimize the effect of ventilation, the windows of each test vehicle were kept closed, with the temperature level and blower speed set to the personal comfort level of the occupants. Drivers maintained a speed characteristic of surrounding traffic by using the "floating car technique."[21] The average test vehicle speed for a given run over a given link was determined from a one-time distance measurement of the link and a computation of the time necessary to traverse the link in minutes and seconds.

Sources of CO associated with the test vehicles were eliminated in two ways. First, the drivers and data collectors refrained from smoking during commutes. Second, all test vehicles were examined and verified to

be free of CO intrusion from exhaust leaks into the passenger compartments from engines and/or tail pipes.

Battelle employed a portable CO monitoring system that consisted of a modified General Electric (GE) CO Detector (Model 15ECS3C03) and a HP-41CV programmable calculator. As described by Fitz-Simons and Sauls,[22] this monitoring system could not only collect instantaneous CO concentrations every 10 seconds, but could store the data and then dump the data after a commuter trip to a miniature cassette tape for temporary storage and later transfer to a computer file. The end times for link checkpoints were stored in the main memory of the HP-41CV.

On each survey day, the CO monitoring systems were randomly assigned to four teams each consisting of a driver and a data collector. Each team was assigned two routes, with each route surveyed on alternating work days. For each survey the probe of the monitor was inside the test vehicle. For one survey of each route, two side-by-side monitors were used, with the probe of one monitor inside the vehicle and the other monitor's probe outside the vehicle. If a commute began or ended in a parking garage, a garage CO reading was taken also.

Several quality assurance (QA) procedures were employed by Battelle to maintain the accuracy of the CO data. First, the monitors were calibrated each morning and evening, Monday through Friday of field surveys. Second, colocated monitors were used on 10% of all trips to determine the precision of the monitors. Third, EPA performed a mid-study audit to test the ability of the GE monitors to identify unmarked CO sample mixtures. The results of these QA procedures and tests were generally satisfactory and lend confidence in the CO monitoring data.[11]

APPLICATION OF THE THEORETICAL MODEL

The Washington Study provided most of the data needed by the theoretical model expressed by Equation (13) to describe the exposure of a commuter to CO from motor vehicle exhaust. Each link of a hypothetical commuter route was assumed to be a separate microenvironment. The time that the vehicle spent within the roadway microenvironment (t_R) was the recorded time in seconds that the vehicle took to travel the link. The most limiting variable was the concentration outside the vehicle on the roadway (C_R), which was available for only 150 observations. Average CO exposure inside the vehicle (E) for a given microenvironment had been measured using the portable CO monitoring system.

As the test vehicle crossed from one microenvironment to another, it was assumed that the vehicle carried some residual CO from the previous microenvironment. Thus, the initial CO concentration (C(0)) as the vehicle entered a new microenvironment was approximated by using the average CO exposure measured in the vehicle in the previous microenvironment. For the first link of a trip C(0) was the average CO concentration observed in the vehicle just prior to the start of the trip. The average C(0) was high (above 20 ppm) for the evening trip on Routes 1 and 8, since these routes originated in a parking garage.[11]

Unfortunately, the Washington Study did not provide data on the volume (V) of nor the air flow rates (F) through the test vehicles. Such data were needed to calculate the time constant (T). Therefore, estimates of T were made using parameters estimated by Ott and Willits[9] for a 1974 VW 412 (Squareback), whose passenger compartment volume was proportional to the 1983 Chevrolet Malibu used in the Washington Study.

Ott and Willits drove their test vehicle through heavy traffic, establishing a relatively high concentration inside the vehicle. Then they turned onto a quiet residential street and monitored the CO concentration in the vehicle as it decayed exponentially. The time constant (T) was calculated as the slope of the least-squares line through the plot of the logarithm of CO (adjusted for the zero-drift of the monitor) versus time. Ott and Willits estimated values of T in this manner under various rates of air flow through the vehicle, represented by different vehicle speeds and window positions.

Given that the windows of test vehicles in the Washington Study were closed during each survey, one is particularly interested in values of T estimated by Ott and Willits under similar conditions. With such estimates of T, one could use linear regression to define a function to estimate values of T appropriate to the Washington Study. Unfortunately, for closed windows Ott and Willits provided only two values of T upon which such a function could be defined. One value of T was estimated to be 0.710 hours when the vehicle speed (U_V) was zero (vehicle parked). A second value of T was estimated to be 0.076 hours at 20 mph.

Although an infinite number of curves could go through these two points, the function chosen should: (1) fit the points provided by Ott and Willits; (2) have a maximum when the vehicle is parked (U_V=0); and (3) decrease with increasing vehicle speed, becoming asymptopic to zero. One type of function that could meet these three criteria is the negative exponential (decay) function of the form:

$$T = Ae^{-BU_V} \tag{15}$$

Given: (1) that T = 0.710 at U_V = 0; (2) that the constant value (A) is equal to 0.710.; and (3) that T = 0.076 hours when U_V = 20 mph, one can then solve for the exponent (B). Substituting the values for A and B into Equation (15) and multiplying the entire relationship by 3600 to convert the units of T from hours to seconds, the following function was developed to provide values of the time constant for various vehicle speeds:

$$T = (.710e^{-.1117U_V}) * 3600 \tag{16}$$

EVALUATION OF THE THEORETICAL MODEL

The evaluation of the theoretical model of Equation (13) focused on three issues. The first issue addressed how well this model predicted observed commuter CO exposures. The second issue concerned the explanatory power of this model compared to a more parsimonious model of commuter exposure, Equation (14). The third issue weighed the importance of considering initial concentrations inside a vehicle's passenger

compartment. These three issues are discussed below. In each case reference is made to Table I, which provides summarized regression statistics associated with the least-squares line of observed values of average CO exposure with values of average CO exposure estimated by the indicated equation.

Predictive Power

The plot of the observed average CO exposure with average CO exposures estimated with Equation (13) (Figure 2) suggested a linear relationship. The estimated values correlated well with the observed values ($r=0.86427$) and the coefficient of determination (r^2) indicated that the estimates explained approximately 75% of the variation in observed average exposures.

The slope of the least-squares line (b) was calculated to be 1.03444. A test of the hypothesis that the true value of the slope was zero (H_0: $b=0$) indicated that this hypothesis may be rejected. One can accept the alternative hypothesis that observed CO exposures were linearly related to the estimated values of CO exposures at a level of significance that is less than 0.00005. The 95% confidence interval for the value of the slope allows the assertion that the true slope of the least-squares line is one ($b=1$). The Y-intercept (a) was calculated to be 0.08996. A test of the hypothesis that the true value of the Y-intercept was zero (H_0: $a=0$) indicated that this hypothesis may not be rejected, since its level of significance (0.8716) is greater than a commonly acceptable level of significance ($\alpha = 0.10$). If one can not reject the possibility that the y-intercept is zero ($a=0$) and can assert with a comfortable level of confidence (95%) that the slope is one ($b=1$), then the theoretical model, as expressed by Equation (13), is a good estimator of the average CO exposure experienced by commuters.

Comparison of the Theoretical and Parsimonious Models

Models of commuter exposure developed by Ingalls[1] and Simmon and Patterson[2] assumed that a commuter's average exposure (E) was about equal to the roadway concentration (C_R), as expressed by the parsimonious model of Equation (14). The issue here is whether the parsimonious model is better than the theoretical model in predicting average CO exposures observed in the Washington Study. In comparison, the parsimonious model of Equation (14) neither correlated nor explained variations in observed average exposures as well as the theoretical model of Equation (13). Equation (13) explained over 11% more of the variation in observed values of average CO exposure.

The Importance of Initial Concentrations

The importance of considering initial concentrations at the start of a commuter trip may be evaluated by attempting to apply the Ott and Willits' model to the Washington data. Ott and Willits assumed that the CO concentration within the test vehicle C(0) was zero when the trip started. Although this assumption may have been appropriate in their

study, initial concentrations inside test vehicles in the Washington study were often greater, and sometimes much greater, than zero. If initial concentrations were unimportant, than the theoretical model expressed by Equation (13) would become:

$$E = C_R(1 - (T/t_R)(1 - e^{-t_R/T})) \quad (17)$$

The issue here is whether Equation (17) is better than the theoretical model in explaining average CO exposures observed in the Washington Study. In comparing the statistics for these two models, Equation (17) neither correlated nor explained variations in observed average CO exposures as well as Equation (13). Equation (13) explained over twice as much of the variation in observed values of average CO exposure.

CONCLUSIONS

The U.S. Environmental Protection Agency funded the Washington Commuter Microenvironment Study in 1982 partly in response to the Congressional debate at that time over the CO emission standard. One purpose of the study, which is still in progress, is to develop a microenvironmental model of commuter exposure to motor vehicle exhaust using CO as an indicator pollutant and personal monitors equipped with advanced data loggers to measure and store exposure data. One intent of the model is to aid the EPA in fine tuning the CO emission standard. Another is to demonstrate the validity of the microenvironmental approach to modeling commuter exposure to vehicle exhaust in traffic.

The Washington Study envisions the vehicular passenger compartment and its roadway setting as separate microenvironments. This paper has presented a theoretical model of passenger compartment exposure given roadway concentrations. Using data from the Washington study, the paper has documented the relatively high predictive power of that model. Further, it has demonstrated the model's superior explanatory power over a more parsimonious model which assumes that concentrations in the passenger compartment are equivalent to those on the roadway. The model has also shown the importance of considering initial concentrations in the passenger compartment as the vehicle moves from one microenvironment to another along a trip.

Modeling ambient concentrations in the roadway microenvironment is the remaining task of the Washington Study. That model, which is still under development, will relate roadway concentrations as a dependent variable to several predictor variables, including ambient air quality, meteorological factors, highway configuration (e.g., street canyons), traffic volumes, and motor vehicle emissions.

ACKNOWLEDGEMENTS

The paper is based on research which received financial support from the Environmental Monitoring Systems Laboratory, U.S. Environmental Protection Agency Cooperative Agreement CR 810344-01-4. The conclusions expressed in the paper do not necessarily reflect the views and policies of the EPA, nor does mention of commercial product trade names constitute endorsement or recommendation for use.

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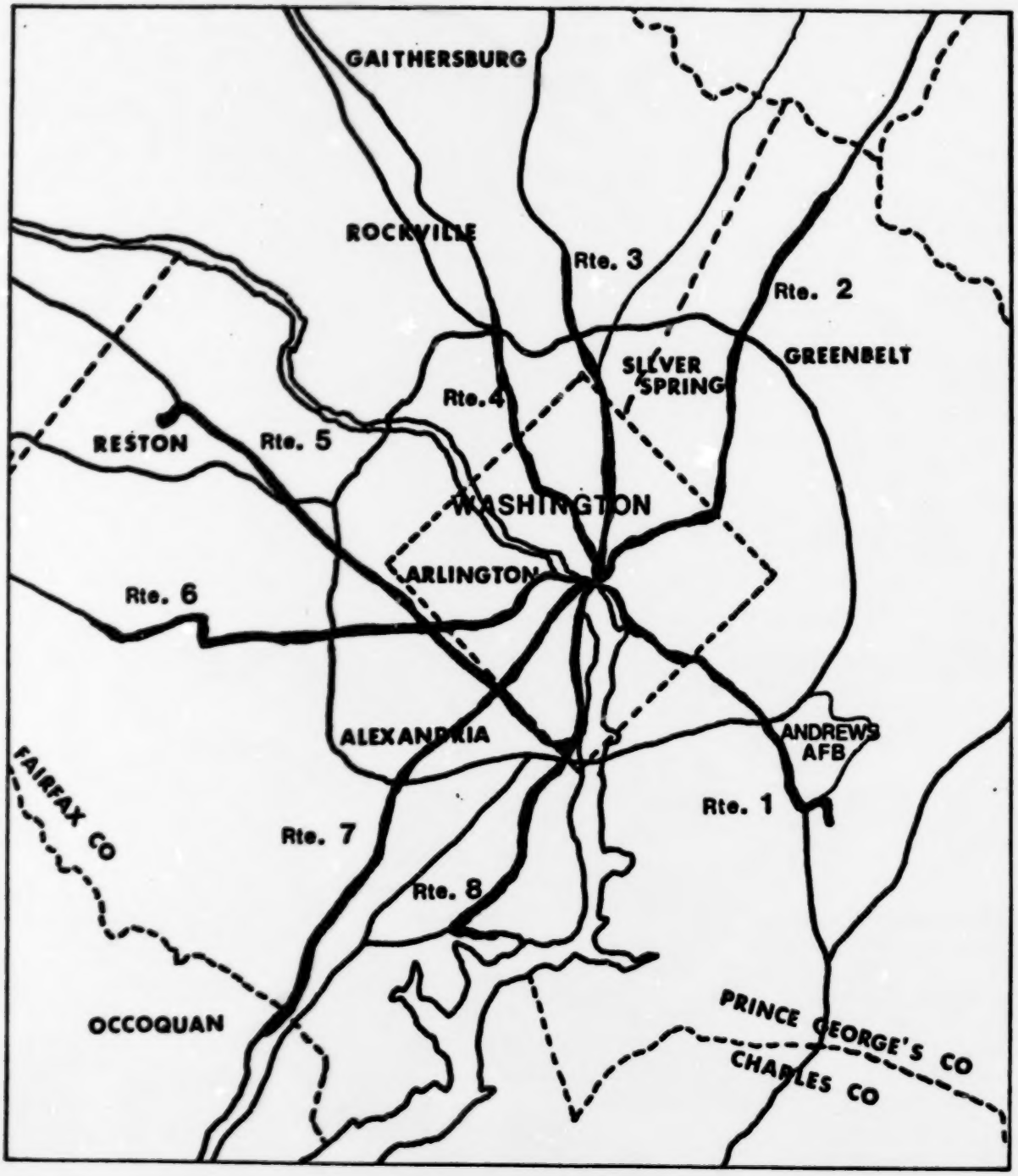

Figure 1. Eight hypothetical automobile commuter routes surveyed in the Washington metropolitan area.

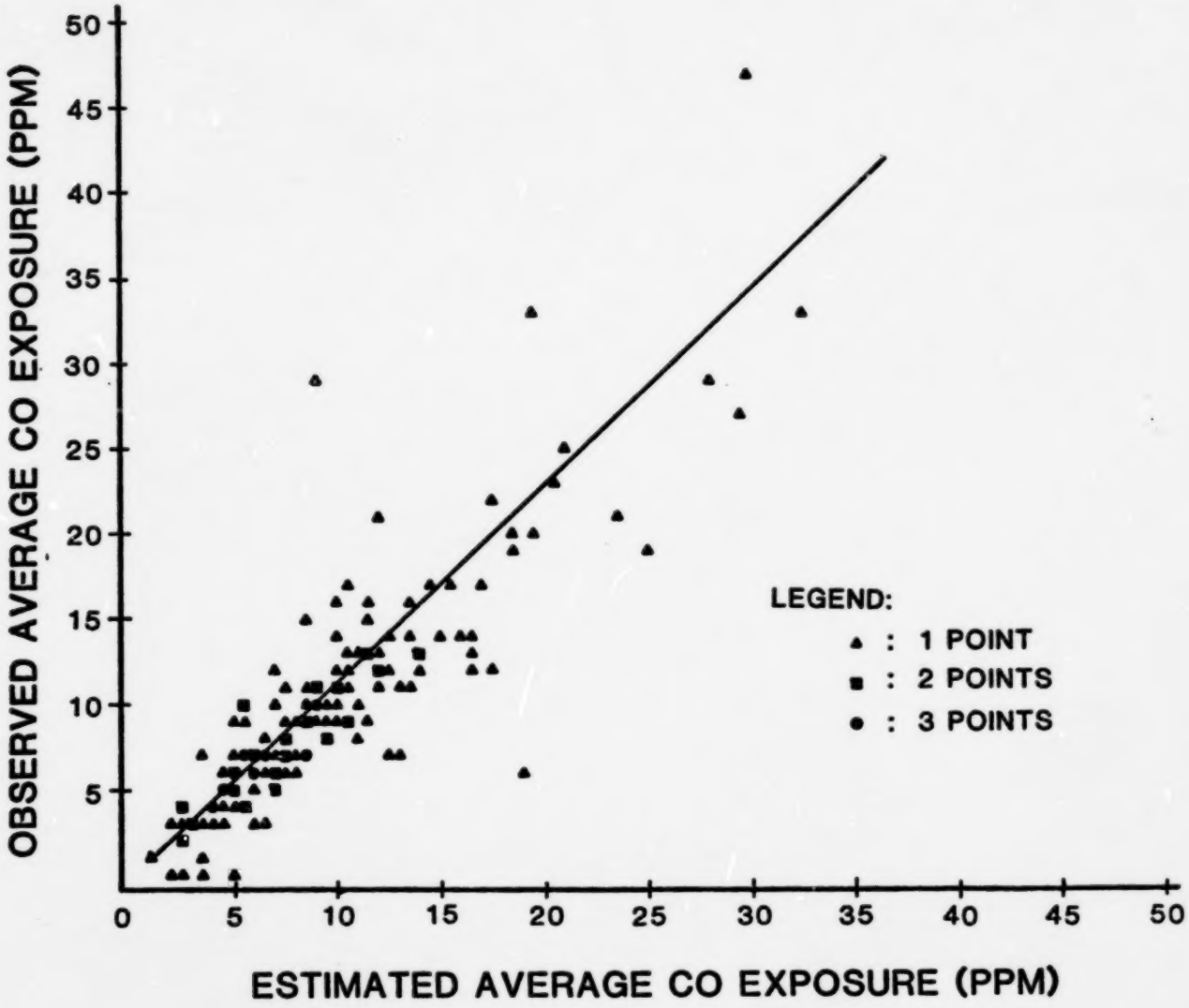

Figure 2. Plot of observed average CO exposures as a function of average CO exposures estimated by Equation (13).

Table I. Statistical summary for evaluating commuter CO exposure models.

	Equation (13)	Equation (14)	Equation (17)
Correlation Coefficient (r)	.86427	.79541	.59048
Coefficient of Determination (r^2)	.74636	.63267	.34867
Slope of Least-Squares Line (b)	1.03444	.85990	1.41776
Level of Significance	.0000	.0000	.0000
95% Confidence Interval			
High	1.18766	.96633	1.73252
Low	.93664	.75346	1.10300
Y-Intercept of Least-Squares Line (a)	.08996	1.43038	4.17718
Level of Significance	.8716	.0269	.0000
95% Confidence Interval			
High	1.18766	2.69533	5.76346
Low	-1.00774	.16543	2.59090
Number of Observations	150	150	150

List of Symbols

Where:

- $C(t)$ = Concentration of CO within vehicle at time, t (ppm).
- $C(0)$ = Initial concentration in vehicle (ppm).
- $C_j(t)$ = Roadway concentration at t, through entry, j (ppm).
- C_R = Concentration on roadway microenvironment (ppm).
- E = Average exposure of commuter (ppm).
- F = Flow rate though vehicle (ft^3/sec).
- $F_j(t)$ = Flow rate into entry, j, at time, t (ft^3/sec).
- $F_k(t)$ = Flow rate out of exit, k, at time, t (ft^3/sec).
- G = Constant of integration
- J = Number of access points on vehicle.
- j = Access point on vehicle.
- K = Number of exit points on vehicle.
- k = Exit point on vehicle.
- $P(t)$ = Aggregate emission rate within vehicle at time, t (gm/sec).
- T = Time constant for vehicle (sec).
- t = Time (sec).
- t_a = Averaging time (sec).
- t_R = Amount of time vehicle spends in microenvironment (i.e. travel time on road) (sec).
- U_v = Vehicle speed (mph).
- V = Volume of vehicle (ft^3).